AN EFFICIENT LIQUID CRYSTAL DISPLAY DRIVING SCHEME USING ORTHOGONAL BLOCK-CIRCULANT MATRIX

a.

BACKGROUND

The invention relates to a protocol for driving a liquid crystal display, particularly to a driving scheme of liquid crystal display, and more particularly to a special arrangement of the entries of the driving matrix, which results in an efficient implementation of the scheme and a reduction in hardware complexity.

a.

DESCRIPTION OF RELATED ART

Passive matrix driving scheme is commonly adopted for driving a liquid crystal display. For those high-mux displays with liquid crystals of fast response, the problem of loss of contrast due to frame response is severe. To cope with this problem, active addressing was proposed in which an orthogonal matrix is used as the common driving signal. However, the method suffers from the problem of high computation and memory burden. Even worse, the difference in sequencies of the rows of matrix results in different row signal frequencies. This may result in severe crosstalk problems. On the other hand. Multi-Line-Addressing (MLA) was proposed, which makes a compromise between frame response, sequency, and computation problems. The block-diagonal driving matrix is made up of lower order orthogonal matrices. To further suppress the frame response, column interchanges of the driving matrix were suggested in such a way that the selections are evenly distributed among the frame. The complexity of the scheme is proportional to square of the order of the building matrix. Increase of order of the scheme results in complexity increase in both time and spatial domains. The order

increase asks for more logic hardware and voltage levels of the column signal.

SUMMARY

a.

According to the invention there is provided a protocol for driving a liquid crystal display, characterised in that a row (common) driving matrix consists of orthogonal block-circulant matrices.

BRIEF DESCRIPTION OF THE DRAWINGS

DETAILED DESCRIPTION

Liquid Crystal Driving Scheme Using Orthogonal Block-Circulant Matrix

The following shows an order-8 Hadamard matrix.

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \end{bmatrix}$$

As mentioned in the foregoing, because of the computation burden and sequency problem of using active driving, MLA was proposed. To implement an 8-way drive by using 4-line MLA, two order-4 Hadamard matrices are used as the diagonal building blocks of the 8x8 driving matrix. The resulting common driving matrix is as follows:

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 1 & 1 & -1 & -1 & 0 & 0 & 0 & 0 \\ 1 & -1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 \\ 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 \\ 0 & 0 & 0 & 0 & 1 & -1 & -1 & 1 \end{bmatrix}$$

To minimize the sequency problem, another 4x4 orthogonal building block has been proposed. The resulting row (common) driving matrix is as follows:

$$\begin{bmatrix} -1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 1 & -1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & -1 & 1 \\ 0 & 0 & 0 & 0 & 1 & -1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & -1 \end{bmatrix}$$

A general m-way display will have a mxm block diagonal orthogonal driving matrix made up of $m/4$ (assuming that m is an integer multiple of 4) 4x4 building blocks. The actual voltage applied is not necessary ± 1 but a constant multiple of the value (i.e., $\pm k$). To further suppress the frame response, it has been proposed that column interchanges of the row (common) driving matrix such that the selections are evenly distributed among the frame. Using the 8-way drive as example, the following row (common) driving matrix results:

$$\begin{bmatrix} -1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & -1 & 0 & 1 & 0 \\ 1 & 0 & -1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & -1 & 0 \\ 0 & -1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 & -1 & 0 & 1 \\ 0 & 1 & 0 & -1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & -1 \end{bmatrix}$$

In the invention, there is proposed a method of generating orthogonal block-circulant building blocks that result in reduced hardware complexity of the driving circuitry. First of all, an orthogonal block-circulant matric is defined as follows:

Definition: An NMxNM block-circulant matrix B consisting of N MxM building blocks $A_1, A_2, \ldots A_N$ is of the form

$$B = \begin{bmatrix} A_1 & A_2 & \cdots & A_N \\ A_N & A_1 & \cdots & A_{N-1} \\ \vdots & \vdots & \ddots & \vdots \\ A_2 & A_3 & A_N & A_1 \end{bmatrix}$$

It is said to be an orthogonal block-circulant if $B^T B = B B^T = (NM) I_{NM}$.

For example, the following 4x4 matrix is orthogonal block-circulant

In this case, N can be 2 or 4. If N=2, then each A_i is 2x2 matrix. If N=4, then each A_i is

$$\begin{bmatrix} -1 & 1 & 1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \end{bmatrix}$$

a scalar (1 or −1). The orthogonal block-circulant matrix can be used as the diagonal building block of a row (common) driving matrix. By proper column and row interchanges, the resulting driving matrix has a property that each row is a shifted version of preceding rows and can be implemented by using shift registers. The following shows the resulting 8-way drive using 4x4 orthogonal block-circulant matrix after suitable row and column interchanges.

$$\begin{bmatrix} -1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & -1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & -1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 & -1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & -1 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & -1 \end{bmatrix}$$

For higher order B, the choice of the order of sub-block A_i is limited. Some M might result in nonexistence of orthogonal block-circulant B. Let $MN=6$, then M, the order of sub-block, can be 1, 2, or 3. It can be shown that orthogonal block-circulant B can be achieved by $M=2$, 3, but not $M=1$. In general, given that MN is even, it can be shown that orthogonal block-circulant B always exists provided that $M \neq 1$. In the following, two means of generating orthogonal block-circulant matrices are proposed.

The first method is based on theory of *paraunitary* matrix but it by no means generates all orthogonal block-circulant matrices. The second method is a means to identify orthogonal block-circulant matrices by nonlinear programming. Theoretically, it can be used to generate all orthogonal block-circulant matrices.

Generation of Orthogonal Block-Circulant Matrix Using Paraunitary Matrix

Consider order $MxNM$ sub-matrix of B as follows:

$$E = [A_1 \quad A_2 \quad K \quad A_N]$$

Define nxn shift matrix $S_{n,m}$ as follows

$$S_{n,m} = \begin{bmatrix} 0 & I_{m\times m} \\ 0_{(n-m)\times(n-m)} & 0 \end{bmatrix}$$

A paraunitary matrix E of order $MxNM$ satisfies

(i) E is orthogonal, i.e.,

$$EE^T = I$$

(ii) E is orthogonal to its column shift by multiples of M, i.e.,

$$ES_{NM,iM}E^T = 0$$

for $i = 1,2, \ldots ,N-1$.

In general, paraunitary matrices can be represented in a cascade lattice form with rotational angles as parameters.

The following two are two example 2x4 paraunitary matrices.

$$E_1 = \begin{bmatrix} 1 & 1 & -1 & 1 \\ -1 & -1 & -1 & 1 \end{bmatrix}$$

$$E_2 = \begin{bmatrix} -1 & 1 & 1 & 1 \\ 1 & -1 & 1 & 1 \end{bmatrix}$$

We have the following property of paraunitary matrices:

Property: B generated by block-circulating paraunitary E is orthogonal.

Proof: Define mxn recurrent shift matrix $R_{n,m}$ as follows

An *orthogonal block-circulant* matrix B of order $NMxNM$ with $MxNM$ sub-matrix E satisfies

(i) E is orthogonal. i.e.,

$$EE^T = I$$

(ii) E is orthogonal to its recurrent shift by multiples of M. i.e.,

$$ER_{iM,NM}E^T = 0$$

for $i = 1,2, \ldots ,N-1$.

Provided that E is paraunitary, as

$$R_{n,m} = S_{n,m} + S^T_{n-m,n-m}$$

we have

$$ER_{(N+1)M,NM}E^T = E(S_{n,m} + S^T_{n-m,n-m})E^T = ES_{n,m}E^T + ES^T_{n-m,n-m}E^T = 0$$

and that completes the proof. Notice that E is paraunitary is a sufficient but not necessary condition for B to be orthogonal block-circulant. Using E_1 and E_2 as building blocks, we obtain the following orthogonal block-circulant matrices.

$$B_1 = \begin{bmatrix} 1 & 1 & -1 & 1 \\ -1 & -1 & -1 & 1 \\ -1 & 1 & 1 & 1 \\ -1 & 1 & -1 & -1 \end{bmatrix}$$

$$B_2 = \begin{bmatrix} -1 & 1 & 1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \end{bmatrix}$$

Notice that B_2 is orthogonal circulant as well as orthogonal block-circulant. As illustrated before, by using it as the building block of row (common) driving matrix with suitable row and column interchanges, each row is a delay-1 shifted version of preceding row. However, B_1 is orthogonal block-circulant but it is not circulant. By suitable row and column interchanges of the resulting driving matrix, two sets of row (common) driving waveforms are obtained. Within a set, each row is a shifted version of the others.

The complexity of implementation is proportional to the order of the sub-blocks A_i (i.e., M). For NM=4, we observe that M can be 1 or 2. For higher order, M=1 does not result in any circulant B that is orthogonal. Provided M=2, orthogonal block-circulant B always exists and can be generated by 2x2N paraunitary matrices. The driving matrix resulted from B_2 with suitable column interchanges is shown below:

$$\begin{bmatrix} 1 & 0 & 1 & 0 & -1 & 0 & 1 & 0 \\ -1 & 0 & -1 & 0 & -1 & 0 & 1 & 0 \\ -1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ -1 & 0 & 1 & 0 & -1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 1 & 0 & -1 & 0 & 1 \\ 0 & -1 & 0 & -1 & 0 & -1 & 0 & 1 \\ 0 & -1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & -1 & 0 & 1 & 0 & -1 & 0 & -1 \end{bmatrix}$$

Rows 1, 3, 5, 7 and 2, 4, 6, 8 form the two sets within which each row is a shifted version of the others.

Generation of Orthogonal block-circulant Matrix by Nonlinear Programming

An orthogonal block-circulant matrix can be generated by nonlinear programming. The method of steepest descent illustrates this. The method of steepest descent is widely used in the identification of complex and nonlinear systems. The update law – identifying sub-matrix E can be stated as follows:

$$E_{n+1} = E_n + \delta \frac{\partial P}{\partial E}$$

where δ is the step size. P is the cost or penalty function. We set P as follows:

$$P(E) = \sum_{i,j} \left(e_{ij}^2 - 1\right)^2 + \left\| EE^T - I \right\|_F^2 + \sum_i \left\| E R_{[illegible]} E^T \right\|_F^2$$

e_{ij} are the entries of E. $\|\cdot\|_F$ is the Frobenius norm of a matrix. The first summation in the function forces all the entries of E to be ±1. The second one forces E to be orthogonal, while the third summation ensures orthogonal block-circulant property of the resulting E.

List of Order-4 and Order-8 Orthogonal Block-Circulant Matrices

The following is an exhaustion of all 2x4 and 2x8 sub-matrices E with entries ±1 that result in orthogonal block-circulant building block.

Order-4

(1)

$$\begin{bmatrix} 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \end{bmatrix};$$

(2)

$$\begin{bmatrix} -1 & 1 & 1 & 1 \\ 1 & 1 & 1 & -1 \end{bmatrix};$$

(3)

$$\begin{bmatrix} -1 & 1 & -1 & -1 \\ 1 & 1 & -1 & 1 \end{bmatrix};$$

(4)

$$\begin{bmatrix} -1 & -1 & -1 & 1 \\ 1 & 1 & -1 & 1 \end{bmatrix};$$

(5) all alternatives of (1)-(4) generated by

(i) sign inversion (i.e., $-E$);
(ii) row interchange, i.e.,

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} E;$$

(iii) circulant shift of E, i.e.,

$$ER_{4,2}$$

and any combinations of (i)-(iii).

Order-8

(1)

$$\begin{bmatrix} 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 \\ 1 & 1 & 1 & -1 & 1 & -1 & -1 & -1 \end{bmatrix};$$

(2)

$$\begin{bmatrix} 1 & 1 & 1 & -1 & 1 & -1 & -1 & -1 \\ [illegible] \\ 1 & 1 & 1 & 1 & -1 & 1 & 1 & -1 \end{bmatrix};$$

(3)
(4)
(5)
(6)

$$\begin{bmatrix} 1 & 1 & -1 & 1 & -1 & 1 & -1 & -1 \\ [illegible] \\ 1 & 1 & 1 & 1 & -1 & 1 & 1 & -1 \end{bmatrix};$$

(7)

(8)
$$\begin{bmatrix} -1 & 1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & -1 & -1 \end{bmatrix};$$

(9)
$$\begin{bmatrix} -1 & 1 & 1 & 1 & 1 & 1 & 1 & -1 \\ 1 & 1 & -1 & 1 & -1 & 1 & -1 & -1 \end{bmatrix};$$

(10)
$$\begin{bmatrix} -1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 \\ 1 & 1 & -1 & -1 & -1 & -1 & -1 & -1 \end{bmatrix};$$

(11)
$$\begin{bmatrix} -1 & 1 & 1 & -1 & -1 & -1 & -1 & -1 \\ 1 & 1 & -1 & 1 & -1 & 1 & -1 & -1 \end{bmatrix};$$

(12)
$$\begin{bmatrix} 1 & -1 & -1 & 1 & -1 & 1 & -1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & -1 & -1 \end{bmatrix};$$

(13)
$$\begin{bmatrix} 1 & -1 & -1 & 1 & 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & -1 & -1 \end{bmatrix};$$

(14)
$$\begin{bmatrix} 1 & -1 & 1 & -1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & -1 & -1 \end{bmatrix};$$

(15)
$$\begin{bmatrix} 1 & -1 & -1 & 1 & -1 & -1 & -1 & -1 \\ 1 & 1 & 1 & -1 & 1 & -1 & -1 & -1 \end{bmatrix};$$

(16)
$$\begin{bmatrix} 1 & -1 & 1 & -1 & 1 & 1 & -1 & -1 \\ 1 & 1 & 1 & 1 & 1 & -1 & -1 & 1 \end{bmatrix};$$

(17)
$$\begin{bmatrix} 1 & -1 & 1 & 1 & 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 & 1 & -1 & -1 & -1 \end{bmatrix};$$

(18)
$$\begin{bmatrix} 1 & 1 & -1 & 1 & 1 & 1 & 1 & -1 \\ -1 & 1 & 1 & 1 & -1 & 1 & -1 & -1 \end{bmatrix};$$

(19)

$$\begin{bmatrix} 1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \\ -1 & 1 & 1 & 1 & -1 & 1 & -1 & -1 \end{bmatrix};$$

(20)

$$\begin{bmatrix} 1 & 1 & -1 & 1 & 1 & 1 & 1 & -1 \\ 1 & -1 & 1 & 1 & 1 & -1 & -1 & -1 \end{bmatrix};$$

(21)
(22)
(23)
(24)

$$\begin{bmatrix} -1 & 1 & 1 & 1 & 1 & -1 & 1 & 1 \end{bmatrix}$$

[illegible]

$$\begin{bmatrix} -1 & 1 & 1 & 1 & -1 & 1 & -1 & -1 \end{bmatrix};$$

(25)
(26)
(27)

[illegible]

(28) all alternatives of (1)-(27) generated by

(i) sign inversion (i.e., $-E$);
(ii) row interchange, i.e.,

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} E;$$

(iii) circulant shift of E, i.e.,

$$ER_{8,2i}$$

i=1, 2, or 3, and any combinations of (i)-(iii)

Thus using the invention a special arrangement of the entries of driving matrix is proposed. By imposing orthogonal block-circulant property to the building blocks of the row (common) driving waveform, the row signals can be made to differ by time shifts only. Each row can now be implemented as a shifted version of preceding rows by using shift registers. The complexity of the matrix driving scheme is greatly reduced and is linearly proportional to the order of the orthogonal block-circulant building block.